

*High-Energy Nuclear Collisions and the QCD Phase Structure*

# Beam Energy Scan at RHIC

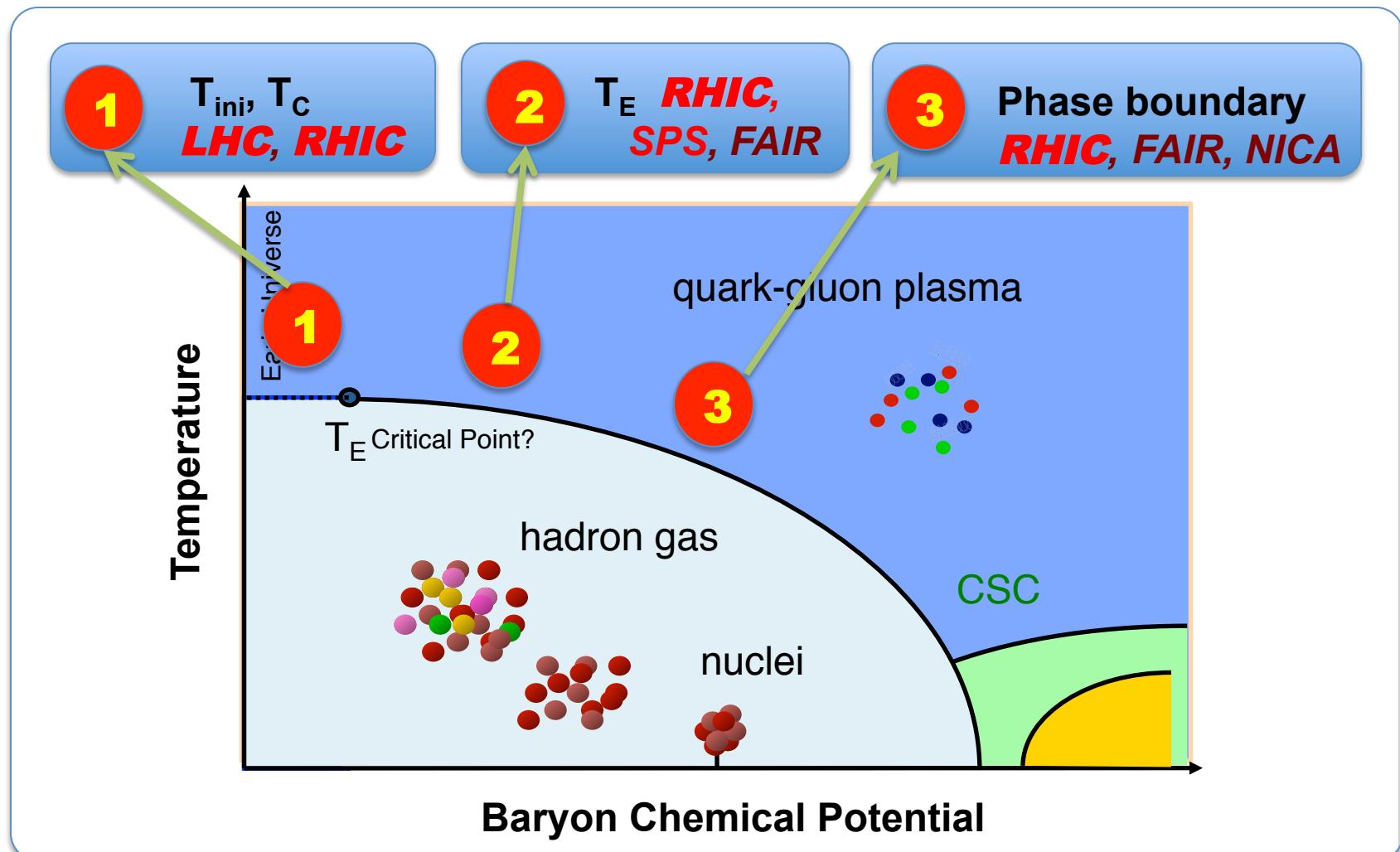
**Nu Xu**

<sup>(1)</sup> *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, USA*

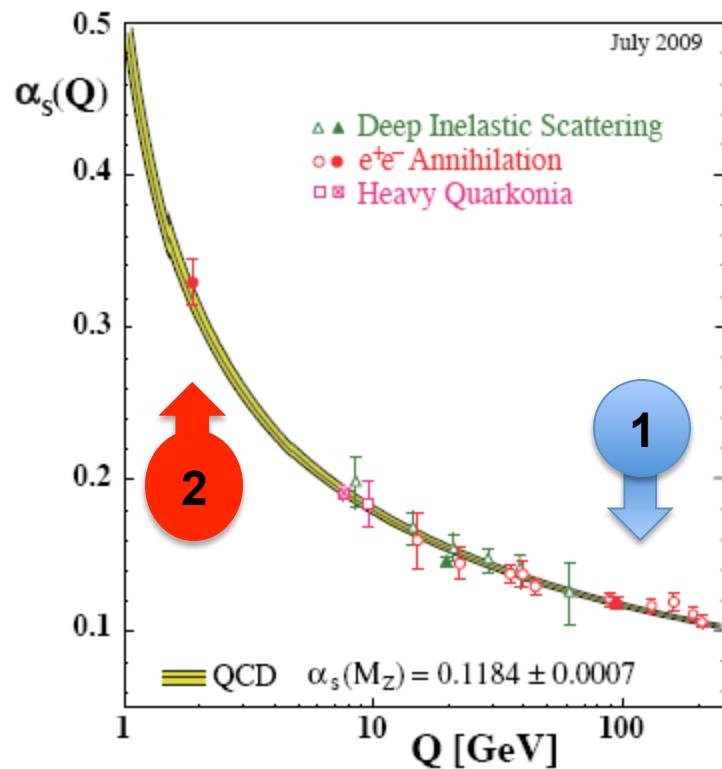
<sup>(2)</sup> *College of Physical Science and Technology, Central China Normal University  
Wuhan, China*



# The QCD Phase Diagram and High-Energy Nuclear Collisions

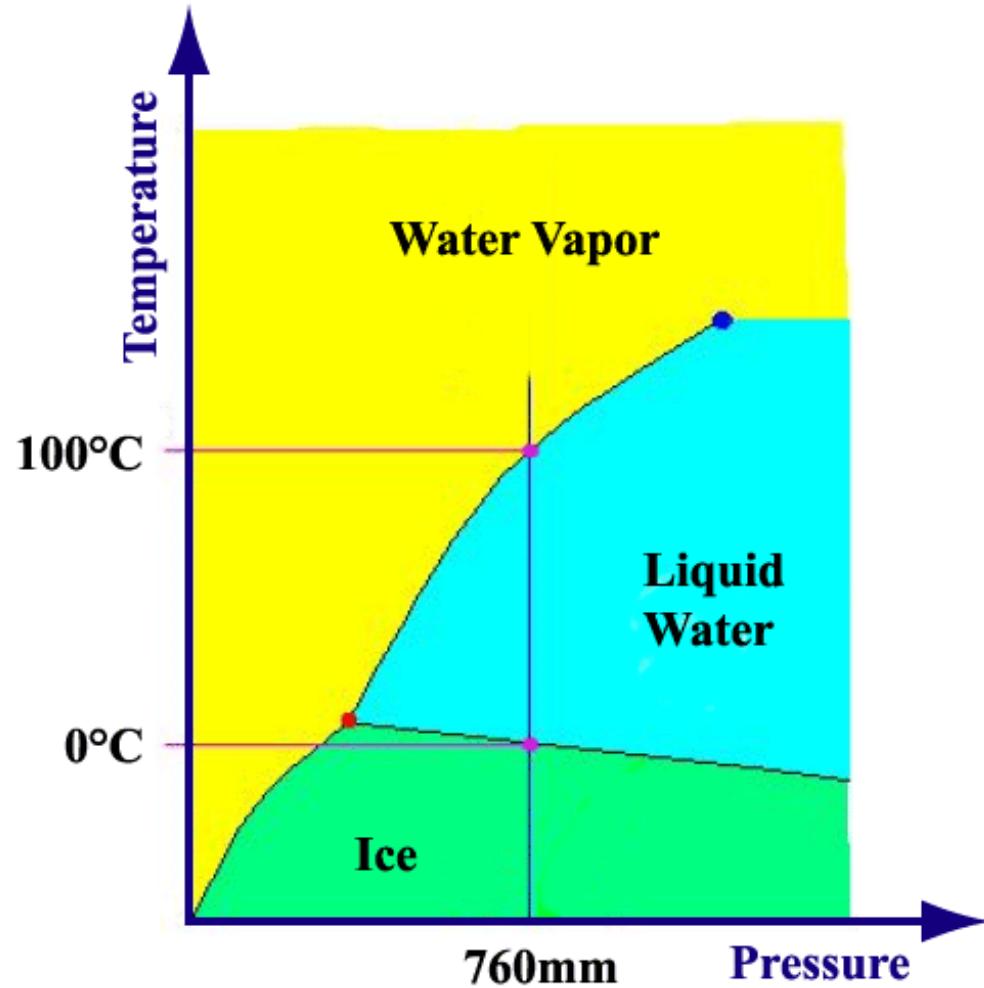


# Asymptotic Freedom



- ① The pQCD coupling becomes small at UV scale: high energy or short distance processes.
- ② Long-distance: structure of matter.  
**Little is known.**

# Phase Diagram: Water

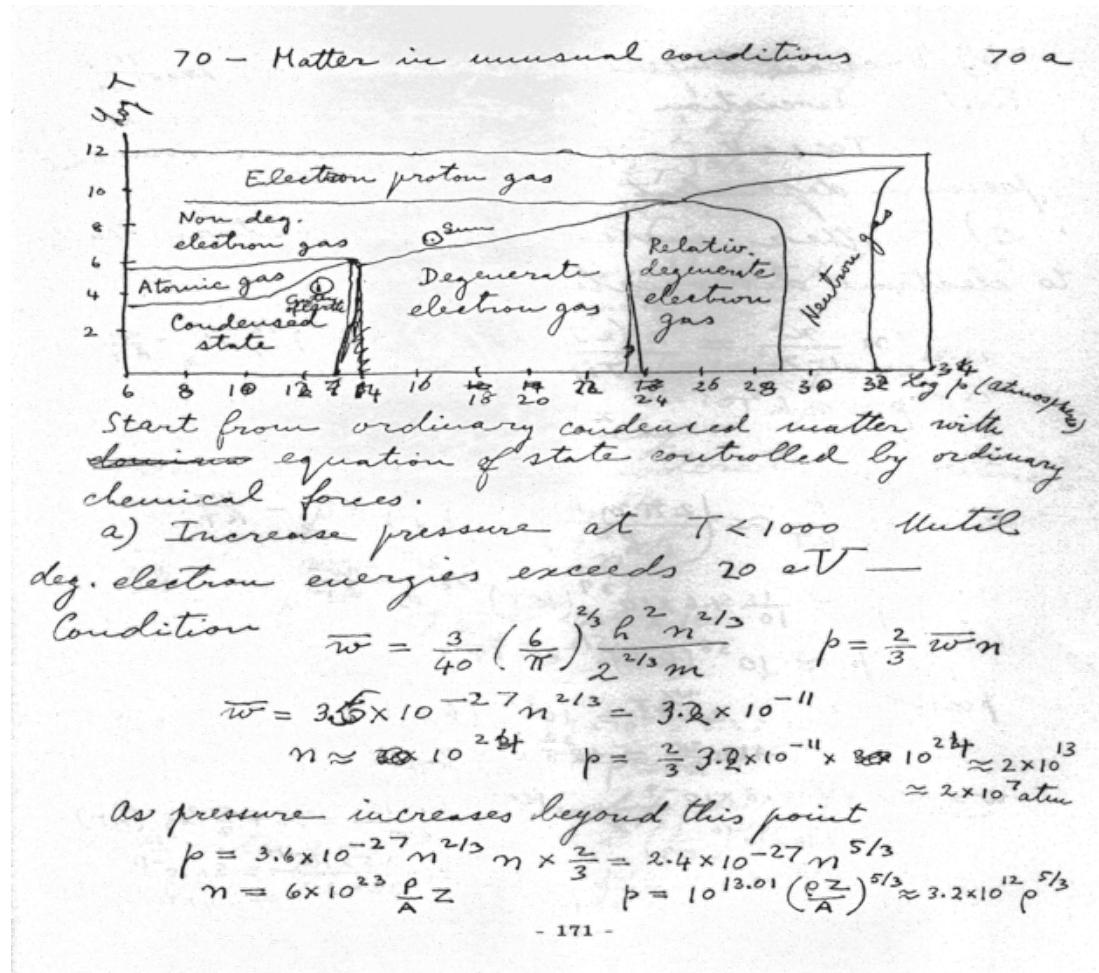


**Phase diagram:** A map shows that, at given degrees of freedom, how matter organize itself under external conditions.

**The QCD Phase diagram:** structure of matter with quark- and gluon-degrees (color degrees) of freedom.

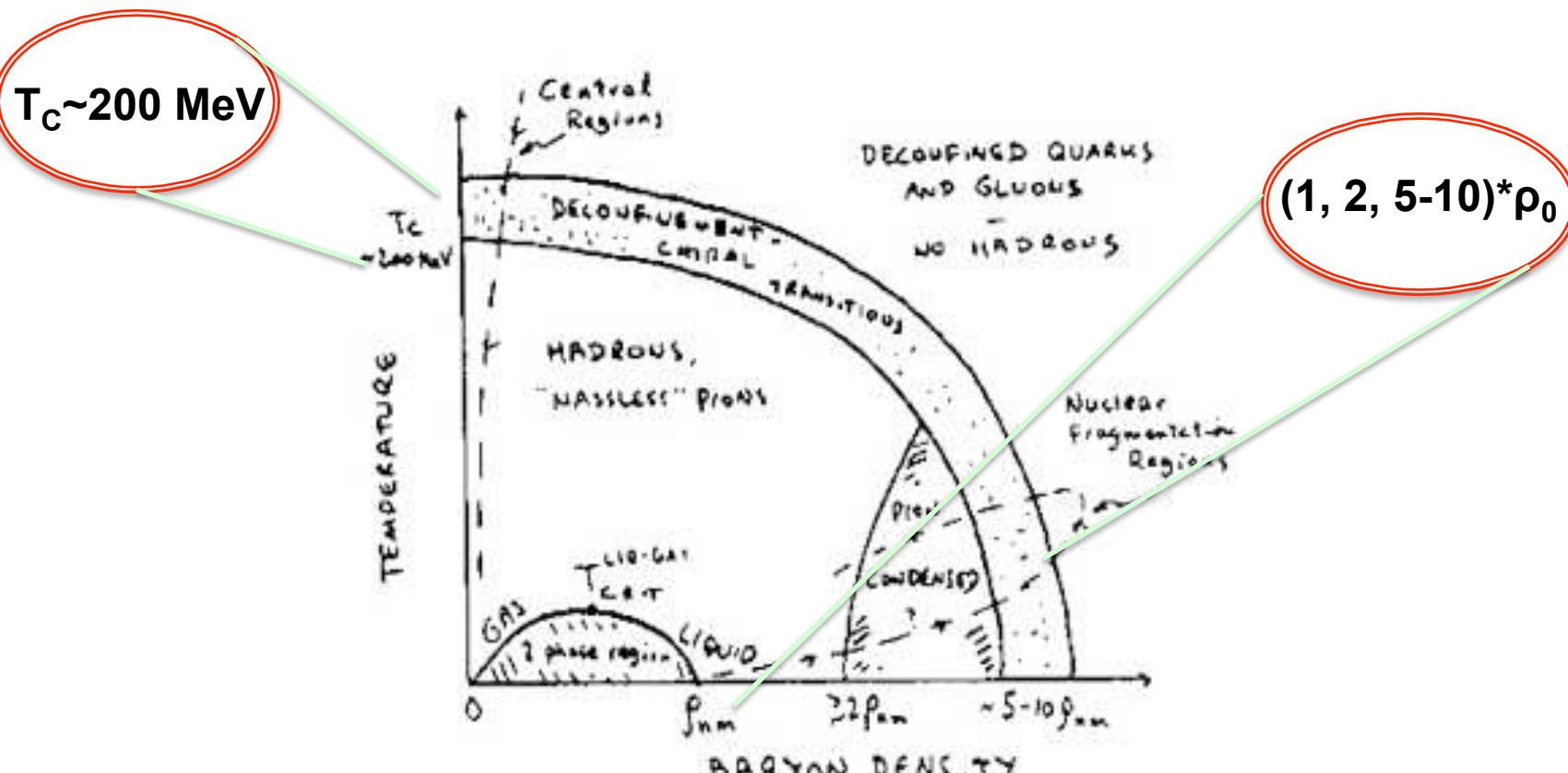
# QCD Phase Diagram (1953)

E. Fermi: "Notes on Thermodynamics and Statistics" (1953)



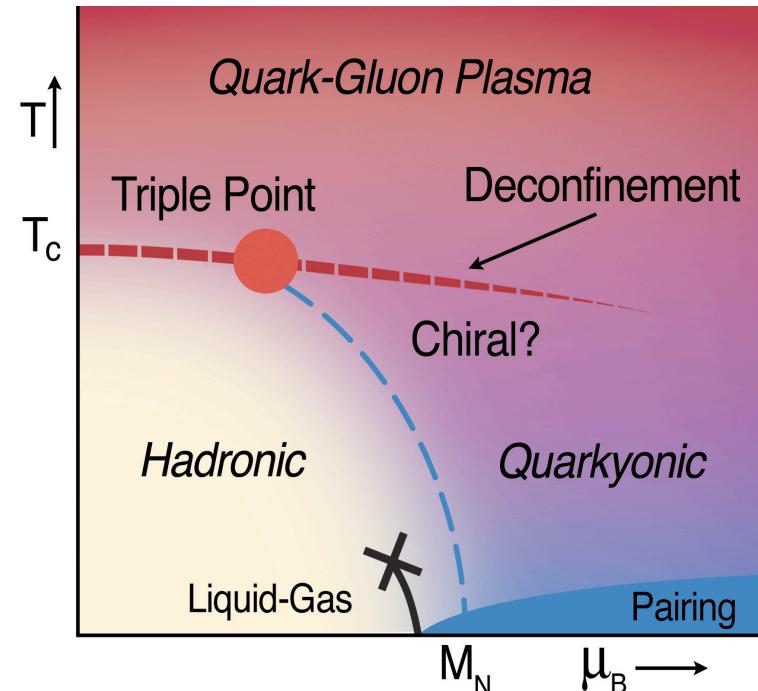
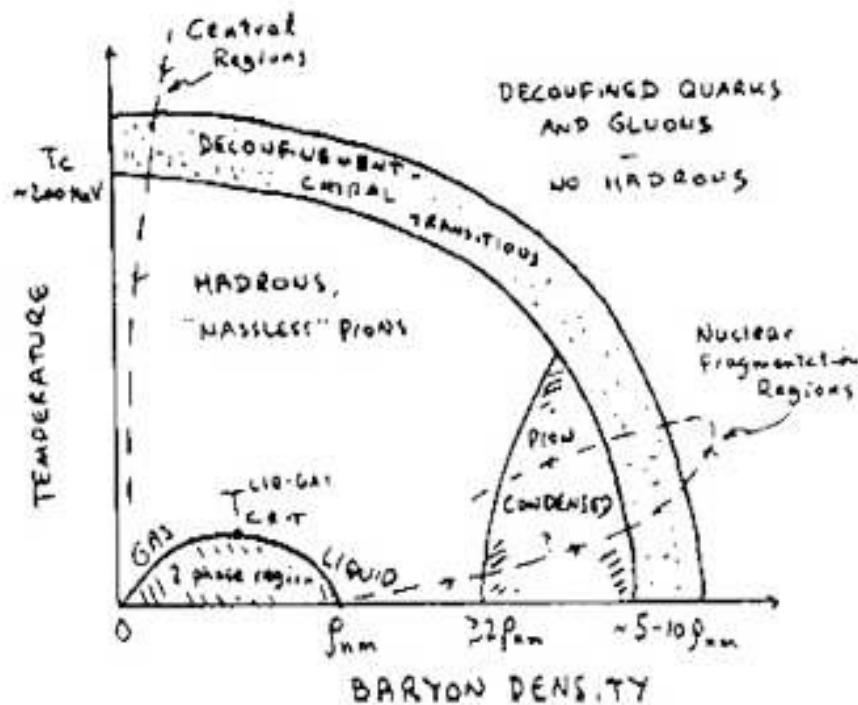
# QCD Phase Diagram 1983

1983 US Long Range Plan - by Gordon Baym



# QCD Phase Diagram (2009)

1983 US Long Range Plan - by Gordon Baym



nucl-th: 0907.4489, NPA830,709(09) L. McLerran

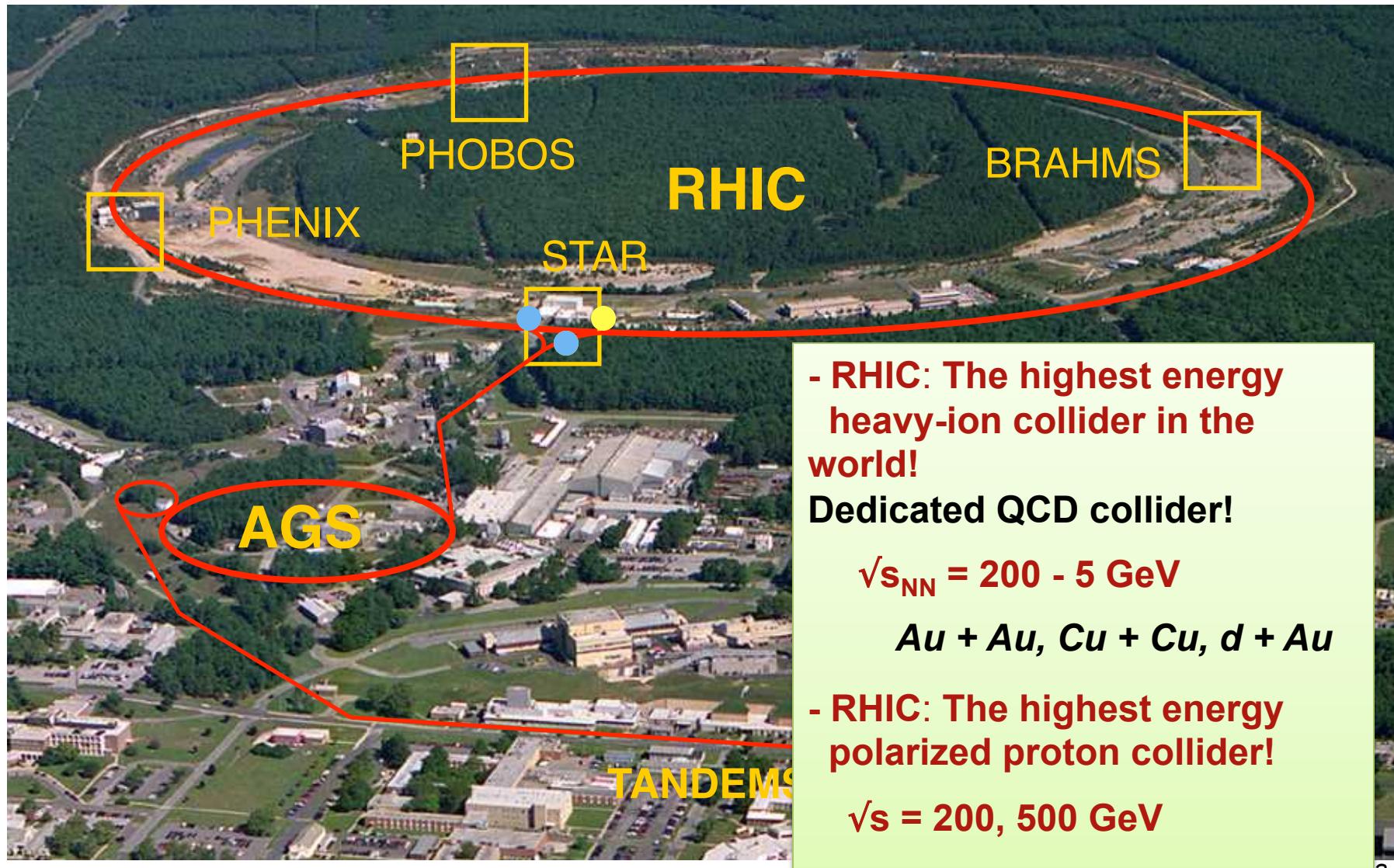
nucl-th 0911.4806: A. Andronic, D. Blaschke, P. Braun-Munzinger, J. Cleymans, K. Fukushima, L.D. McLerran, H. Oeschler, R.D. Pisarski, K. Redlich, C. Sasaki, H. Satz, and J. Stache

**Systematic experimental measurements ( $E_{beam}$ ,  $A$ ) : extract numbers that might be related to the QCD phase diagram!**



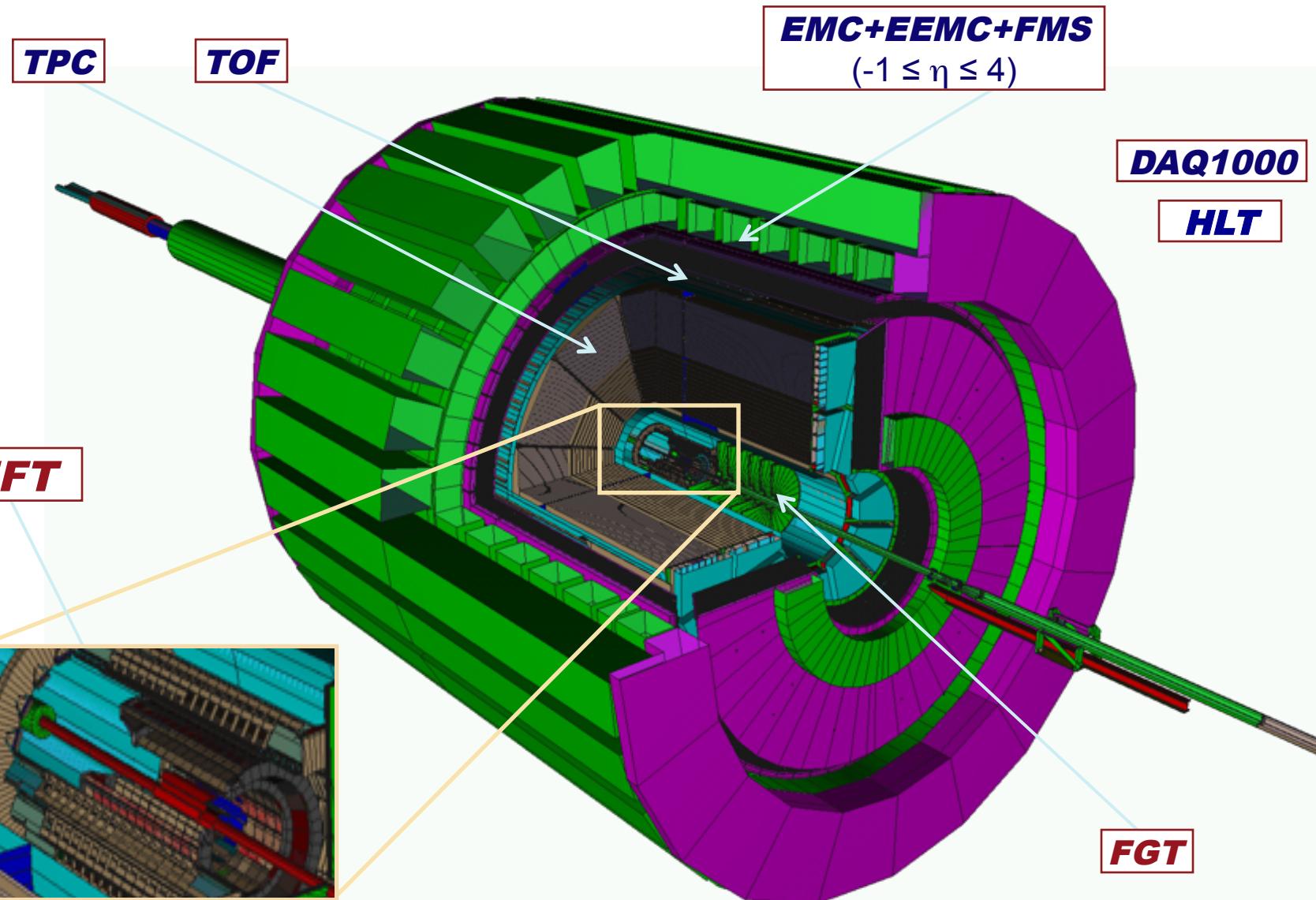
# Relativistic Heavy Ion Collider (RHIC)

Brookhaven National Laboratory (BNL), Upton, NY



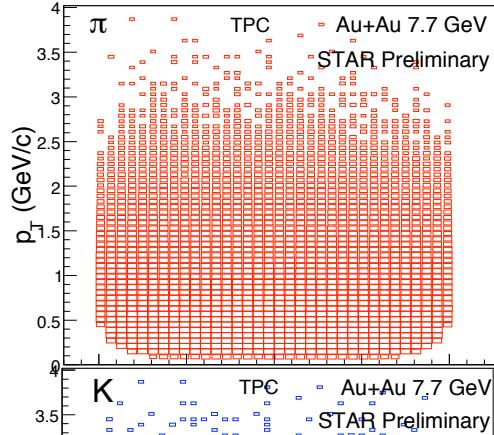


# STAR Detectors: *Full $2\pi$ particle identification!*

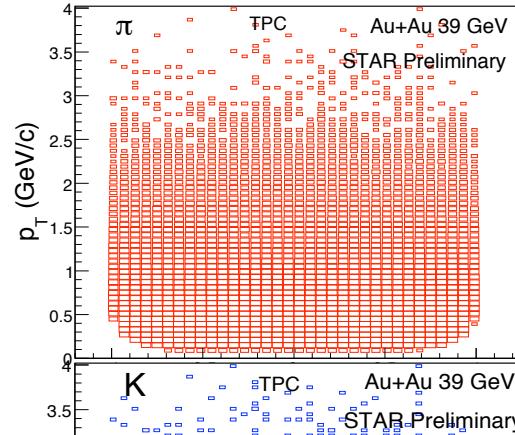


# Particle Identifications & Accept. at STAR

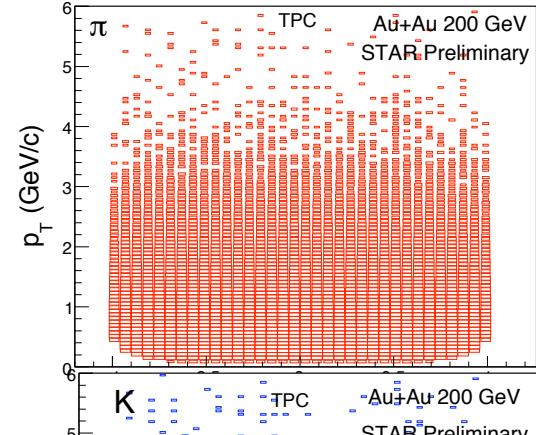
Au+Au at 7.7 GeV



Au+Au at 39 GeV

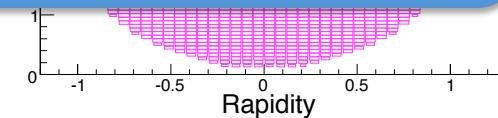
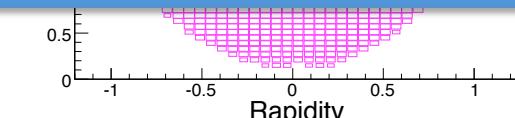
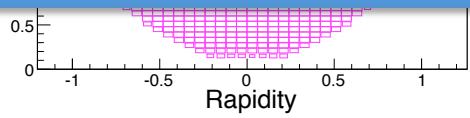


Au+Au at 200 GeV



## Collider Experiments:

- 1) Pros: At mid-rapidity, uniform as a function of beam energy and particle type; Systematic error under control.
- 2) Cons: Low collision rates.





# STAR BES Programs

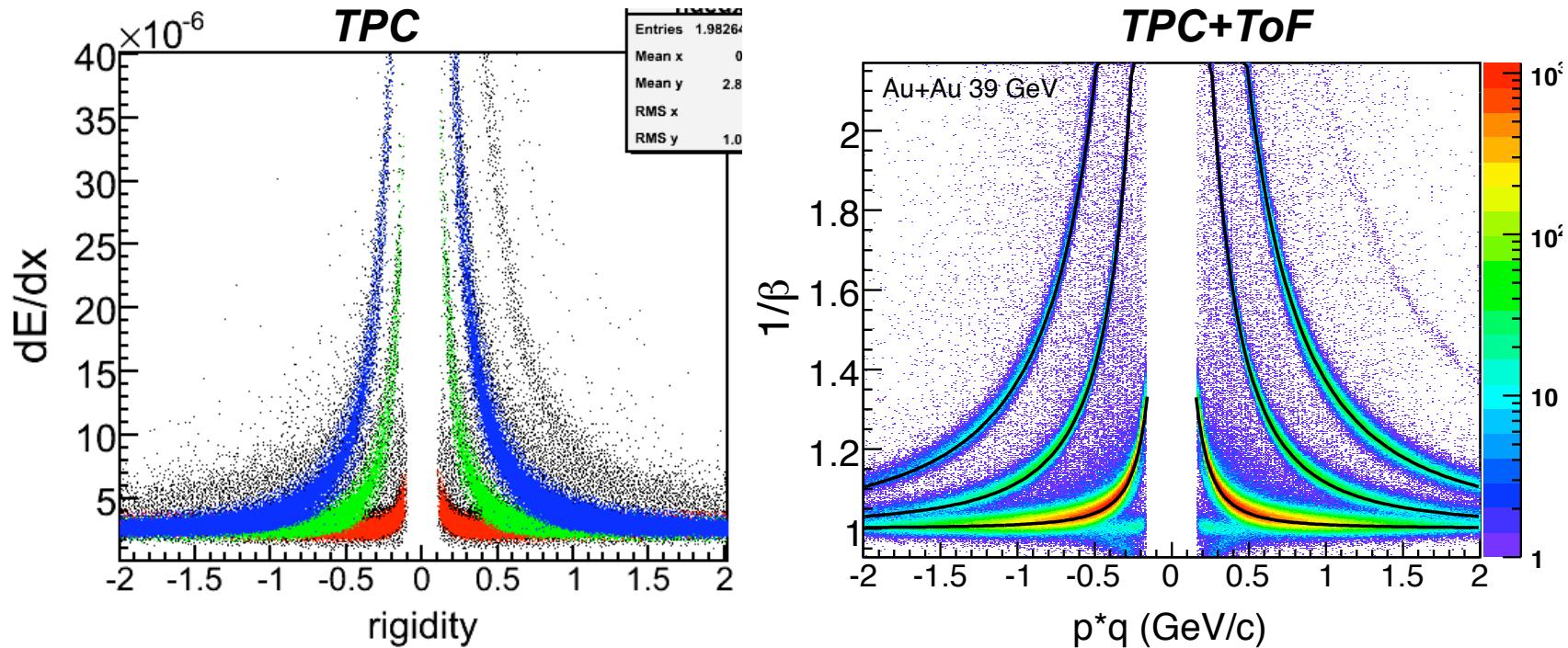


Beam Energy (GeV)	Weeks	# of events	Physics
39	1.5	250M	BES programs (1) QCD $T_E$ (2) QCD phase boundary
27		(33M)	
18		(15M)	
11.5	2	7M	
7.7	5	5M	
5.5	0.5	5 (0.1M)	

Weekly planning info: [http://www.c-ad.bnl.gov/esfd/RMEM\\_10/rhic\\_planning.htm](http://www.c-ad.bnl.gov/esfd/RMEM_10/rhic_planning.htm)

# MRPC ToF Performance

$\sqrt{s_{NN}} = 39 \text{ GeV Au + Au Collisions}$



Beam Energy	Timing Resolution	Remarks
200 (GeV)	85 (ps)	At 39 GeV, using a new calibration scheme without information of start time from VPD, 87 ps of timing resolution has been achieved.
62.4 (GeV)	90 (ps)	
39 (GeV)	85 (ps)	



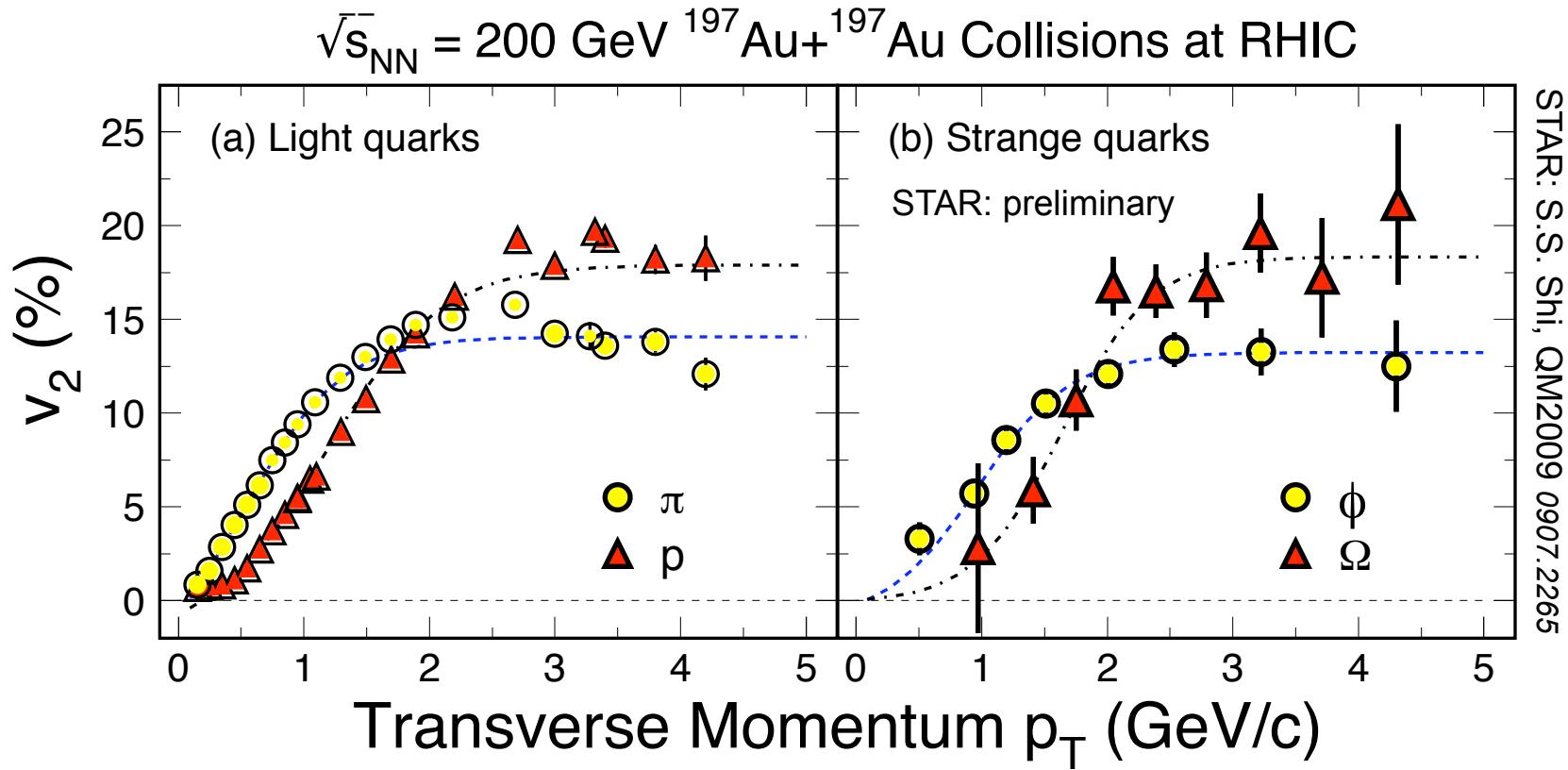
# Au + Au Collisions at RHIC



## Observables:

- 1) Number of quark (NCQ) scaling in  $v_2$ 
  - deconfinement, phase boundary
- 2) Azimuthally dependence of HBT parameters
  - deconfinement, phase boundary, EOS
- 3) Charged hadron correlations – **CME**
  - deconfinement, Chiral symmetry restoration
- 4) High order correlation functions: **B, S, Q**
  - critical point
- 5) Other E-by-E measurements,  **$\langle K^+/\pi^+ \rangle$** 
  - phase boundary(?), critical point(?)
- 6) Di-lepton measure: bulk penetrating probe

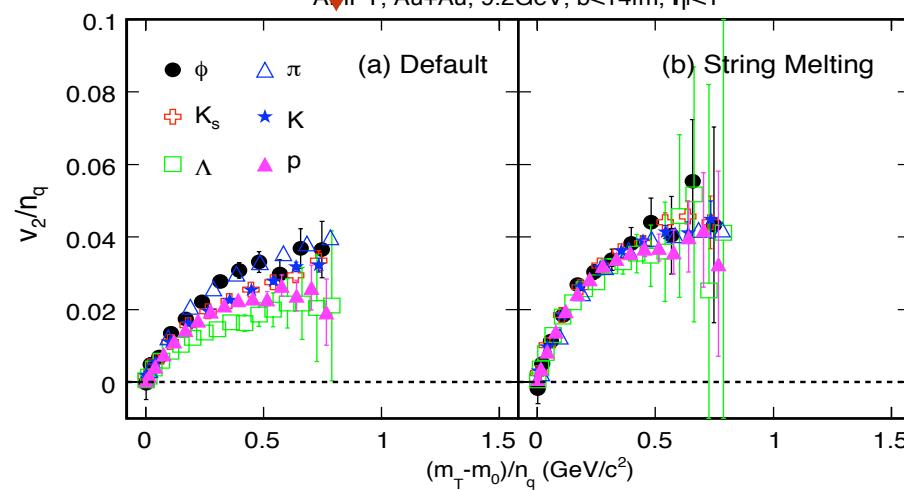
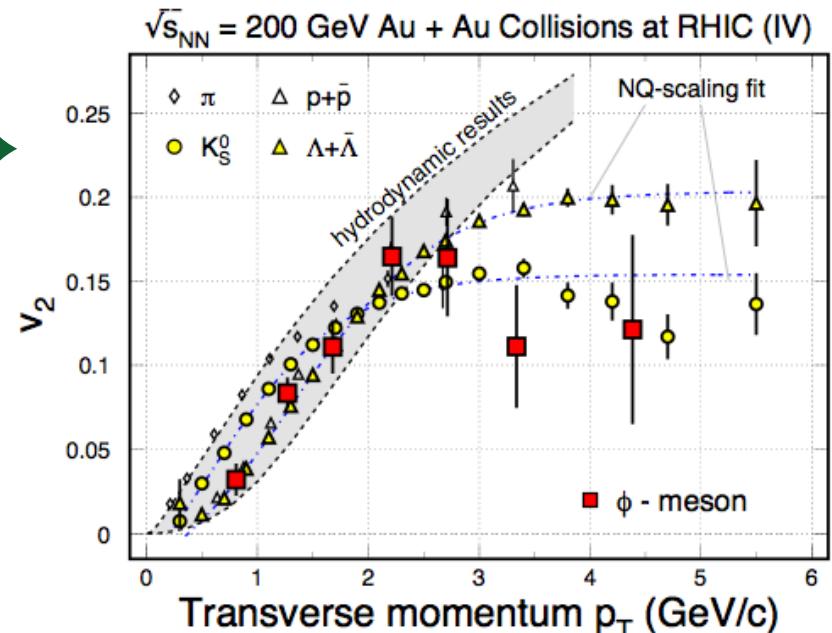
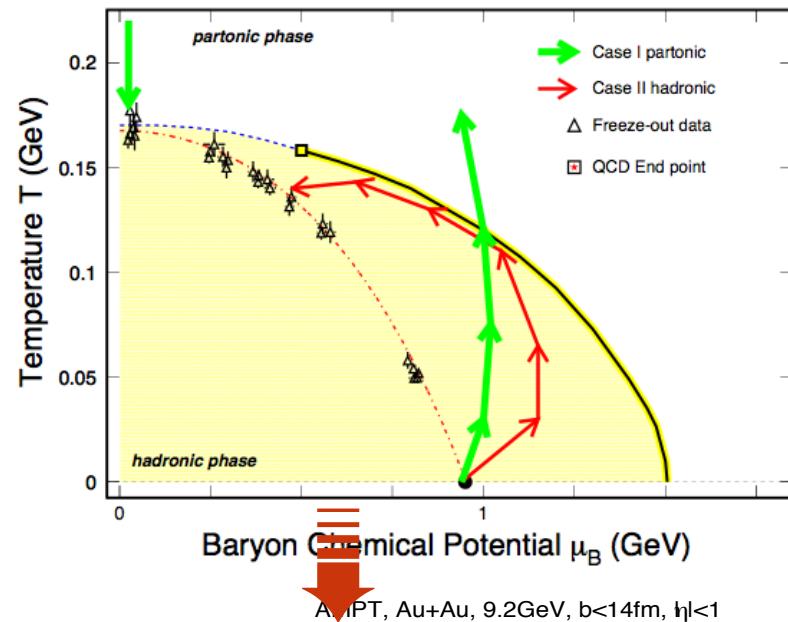
# Partonic Collectivity at RHIC



- Low  $p_T$  ( $\leq 2 \text{ GeV}/c$ ): hydrodynamic mass ordering
- High  $p_T$  ( $> 2 \text{ GeV}/c$ ): number of quarks ordering
- s-quark hadron: smaller interaction strength in hadronic medium
- light- and s-quark hadrons: similar  $v_2$  pattern

**=> Collectivity developed at partonic stage!**

# Observable\*: NCQ Scaling in $v_2$



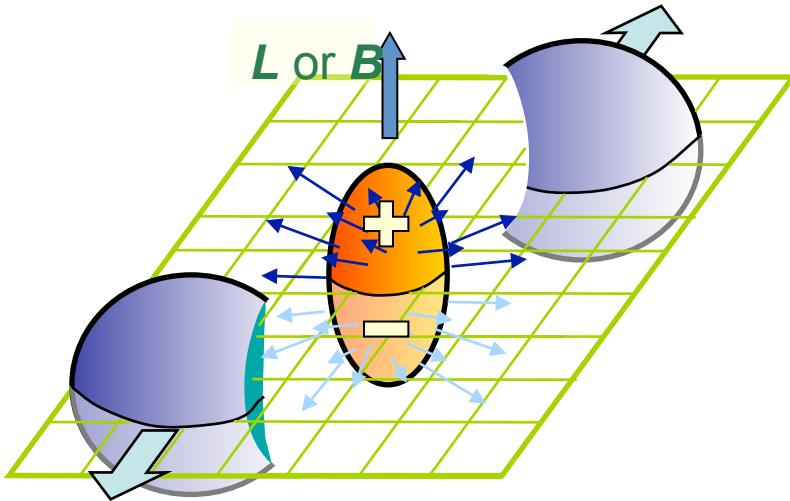
- $m_\phi \sim m_p \sim 1 \text{ GeV}$
- $s\bar{s} \Rightarrow \phi$  not  $K^+K^- \Rightarrow \phi$
- $\sigma_{\phi h} \ll \sigma_{p\pi, \pi\pi}$

**In the hadronic case, no number of quark scaling and the value of  $v_2$  of  $\phi$  will be small.**

\* Thermalization is assumed!

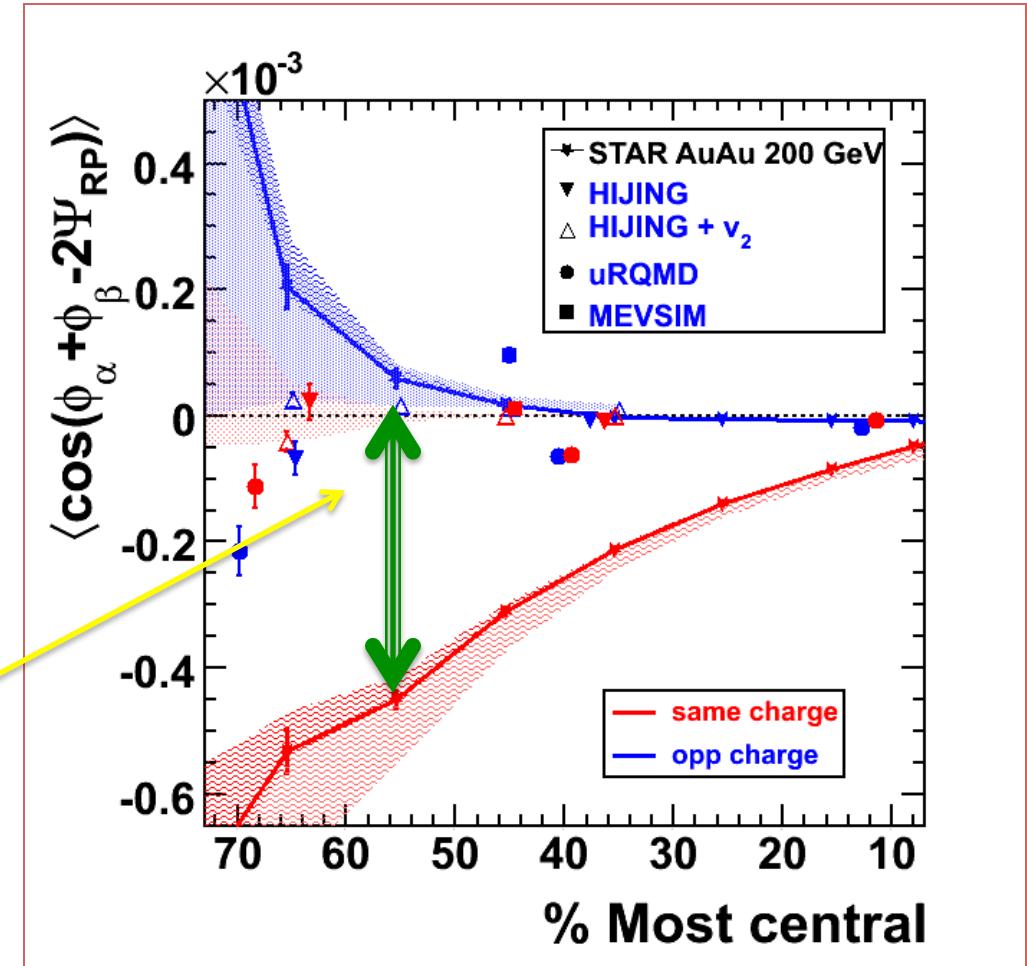
STAR Collaboration: F. Liu, S.S. Shi, K.J. Wu et al.

# Search for Local Parity Violation



*The separation between the same-charge and opposite-charge correlations.*

- Strong EM fields
- De-confinement and Chiral symmetry restoration



Voloshin, PR C62, 044901(00).

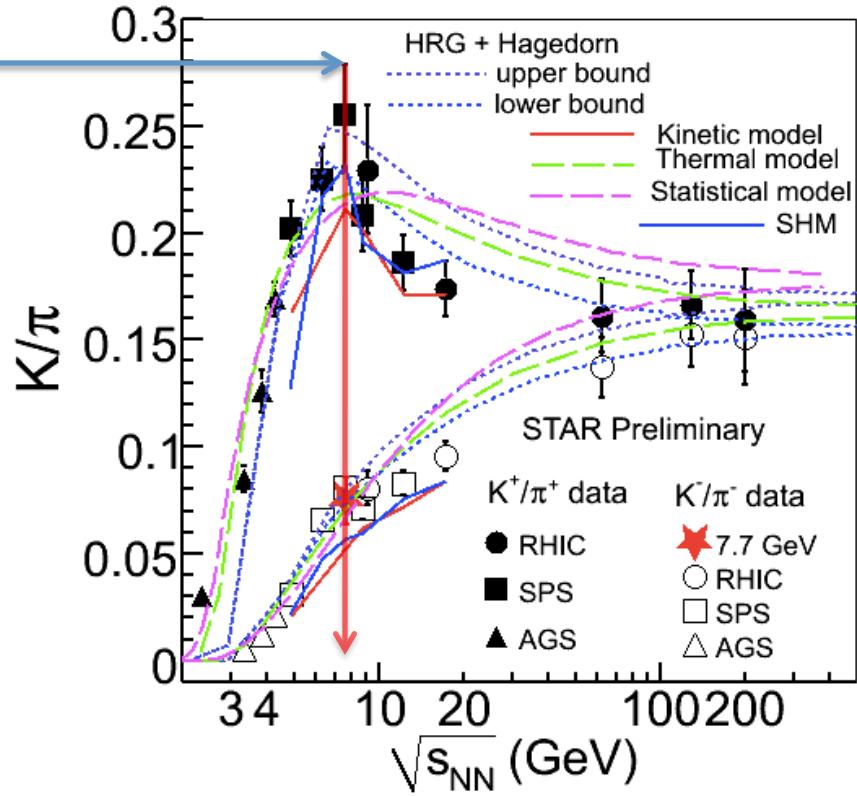
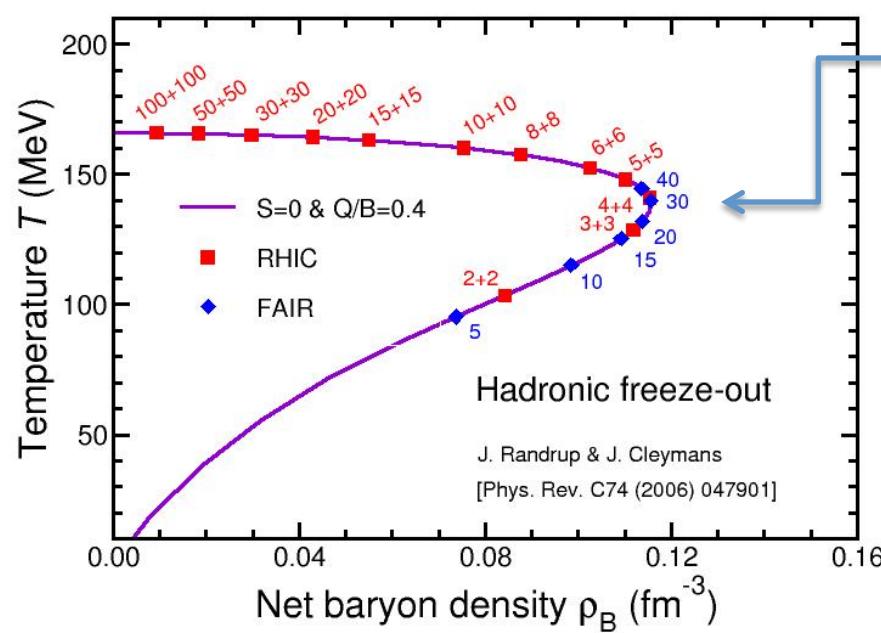
STAR; arXiv: 0909.1739 (PRL); 0909.1717 (PRC).

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# Remarks on CBM Energy Region

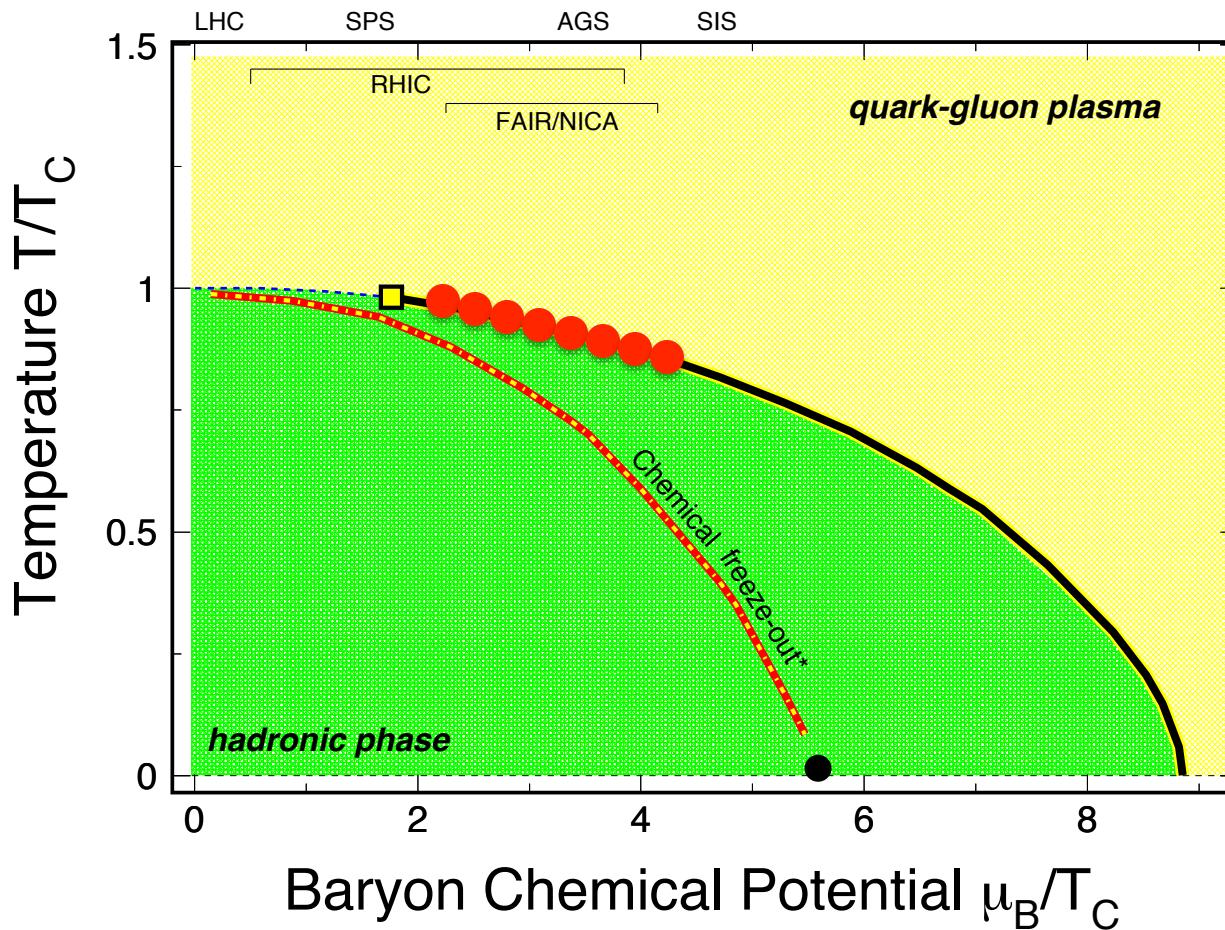
$$5 < \sqrt{s_{NN}} < 11 \text{ GeV}$$

# Maximum Baryon Density



The maximum baryon density at freeze-out:  $\sqrt{s_{NN}} \sim 8 \text{ GeV}$

# Observables for CBM



- 1) High order correlations: B, S, Q  $\Leftrightarrow$  phase transition, critical point
- 2) Di-electron measurements  $\Leftrightarrow$  EOS, dof
- 3)  $\phi$ -meson distributions  $\Leftrightarrow$  sensitive to non-hadronic effect
- 4) Systematic measurements of collectivity
- 5) ...